

Observation of photonic chiral edge states in penrose quasicrystals

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Abstract: Photonic chiral edge states with one-way propagation and robust topological protection are hallmark features of photonic Chern insulators. To date, photonic chiral edge states have been observed in two-dimensional (2D) periodic and amorphous gyromagnetic photonic crystals. Recent theoretical studies reveal that photonic chiral edge states can also exist in 2D Penrose quasicrystals with long-range order but lack translational symmetry. Here, we report the first experimental observation of photonic chiral edge states in a 2D Penrose-tiled gyromagnetic photonic quasicrystal. By using microwave measurements, we observe a complete photonic band gap in the Penrose photonic quasicrystal despite the absence of bulk Bloch bands in momentum space. Moreover, we directly observe unidirectional backscattering-immune photonic chiral edge states within the photonic bandgap of the 2D Penrose quasicrystal. These results broaden our understanding of photonic chiral edge states and provide a new platform for exploring the intriguing properties of topological photonic quasicrystals.

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1. Introduction

Recently, the photonic realization of the celebrated Haldane model [1] inspired the first two-dimensional (2D) photonic Chern insulator [2–4] hosting unidirectional backscattering-immune photonic chiral edge states, and subsequently sparked the emerging field of topological photonics [5–9]. Due to its robust topological protection against sharp bends, defects, and disorders, photonic Chern insulators associated with their photonic chiral edge states have exhibited promising and wide applications in topological waveguiding [3,4,10,11], topological lasing [12–14], topological slow-light [15–18], topological nonlinear frequency mixing [19], and topological cavities [20,21]. To date, the vast majority of photonic Chern insulators [4,11,22,23] have been realized in periodic gyromagnetic photonic crystals which possess both long-range and short-range positional orders. Consequently, their unique topological properties can be characterized by an integer topological invariant (Chern number) calculated by integrating the Berry curvatures on the 2D Brillouin torus, which in turn owe its existence to the discrete translational symmetry of the period lattices [24,25].

In addition to the periodic photonic Chern insulators, there are gyromagnetic photonic materials without periodicity, such as amorphous gyromagnetic photonic crystals with no long-range order but only short-range order [26–29], and gyromagnetic photonic quasicrystals that exhibit long-range periodicity without translational symmetry [30]. Due to the absence of discrete translational symmetry and topological Bloch band theory, it is natural to ask whether these nonperiodic gyromagnetic photonic materials can support photonic chiral edge states. Some

authors have theoretically [26,27] and experimentally [28] demonstrated that photonic chiral edge states can exist in photonic amorphous topological insulators without lattice periodicity. Moreover, recent theoretical work has predicted that nontrivial topological band gaps and robust photonic chiral edge states can also exist in a topological photonic quasicrystal composing gyromagnetic rods under external magnetic fields [30]. However, so far the experimental observation of photonic chiral edge states in a gyromagnetic photonic quasicrystal has remained elusive.

Here, we report the first experimental observation of photonic chiral edge states in a 2D Penrose photonic quasicrystal consisting of gyromagnetic rods sandwiched between permanent magnets to break time-reversal symmetry. By performing microwave edge transmission and near-field imaging measurement, we directly observe unidirectional and robust photonic chiral edge states in a 2D Penrose gyromagnetic photonic quasicrystal. Our work extends the research scope of photonic Chern insulators and paves the way for exploring nontrivial topological states in photonic quasicrystals.

2. Design of topological photonic quasicrystals

To construct a topological photonic quasicrystal with nontrivial topological band gaps and photonic chiral edge states, we start with a decagonal pattern based on the Penrose tiling consisting of two types of rhombuses. Specifically, these two kinds of rhombuses have the same edge length $a = 20$ mm and different angles (the thin rhombuses contain 36 and 144 degrees, while the thick rhombuses contain 72 and 108 degrees), as shown in Fig. 1(a). The vertices of each rhombus are shown in Fig. 1(b), at which we can put photonic building blocks to construct photonic quasicrystals. In this work, we put gyromagnetic rods (radius $r = 2.8$ mm and height $h = 5$ mm) sandwiched between two permanent magnets (radius $r = 2.8$ mm and height $h = 1$ mm) at each vertex to construct the topological gyromagnetic photonic quasicrystal with broken time-reversal symmetry, as shown in Fig. 1(c).

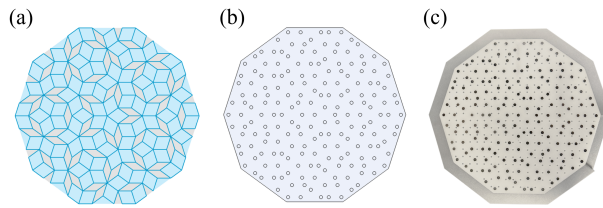


Fig. 1. Penrose tiling and the construction of gyromagnetic photonic quasicrystals based on this tiling. (a) A finite decagonal structure based on Penrose tiling which consists of two types of rhombus. (b) Top view of the topological photonic quasicrystal by placing gyromagnetic rods sandwiched between two permanent magnets at the vertices of the tiling. (c) Photography of the fabricated sample of the topological gyromagnetic photonic quasicrystal whose boundaries are surrounded by aluminum.

These gyromagnetic rods are yttrium iron garnet (YIG) ferrite materials with a permittivity of approximately $\varepsilon = 15$. When external magnetic fields are applied to the YIG rods to break the time-reversal symmetry, imaginary off-diagonal terms are added to the permeability tensor of the YIG rods,

$$\tilde{\mu} = \begin{bmatrix} \mu_r & i\kappa & 0 \\ -i\kappa & \mu_r & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad (1)$$

where $\mu_r = 1 + \frac{(\omega_0 + i\alpha\omega)\omega_m}{(\omega_0 + i\alpha\omega)^2 - \omega^2}$, $\kappa = \frac{\omega\omega_m}{(\omega_0 + i\alpha\omega)^2 - \omega^2}$, $\omega_m = \gamma\mu_0 M_s$, $\omega_0 = \gamma\mu_0 H_0$, $\mu_0 H_0$ is the external magnetic field (about 0.13 Tesla) along the z direction, $\gamma = 1.759 \times 10^{11} \text{ C/kg}$ is the gyromagnetic ratio, $\alpha = 0.0088$ is the damping coefficient and ω is the operating frequency [31].

We then calculate the eigenmode spectrum of the topological gyromagnetic photonic quasicrystal with perfect electric conductor (PEC) boundary conditions, as shown in Fig. 2(a), which consists of bulk states (grey dots) and edge states (blue dots) within the photonic band gap (grey region). To show these are indeed bulk states and edge states, we plot their electric field intensity distributions in Figs. 2(b)–2(c), respectively, from which we can see that the bulk states penetrate the whole bulk while the edge states are mainly confined around the edges of the gyromagnetic photonic quasicrystal. To further demonstrate the topological edge states within the photonic band gap are indeed unidirectional backscattering-immune photonic chiral edge states, we place a point source (blue star) at the edge of the gyromagnetic photonic quasicrystal to excite the edge states and insert a PEC obstacle in the propagation path, as shown in Fig. 2(d). It can be seen that the photonic chiral edge states propagate unidirectionally and circumvent the PEC obstacle without any backscattering. Note that the photonic chiral edge states do not form a close loop as that in Fig. 2(c) because we sent one edge of the gyromagnetic photonic quasicrystal as the perfect absorption boundary (blue line) to demonstrate the one-way propagation property of the photonic chiral edge states.

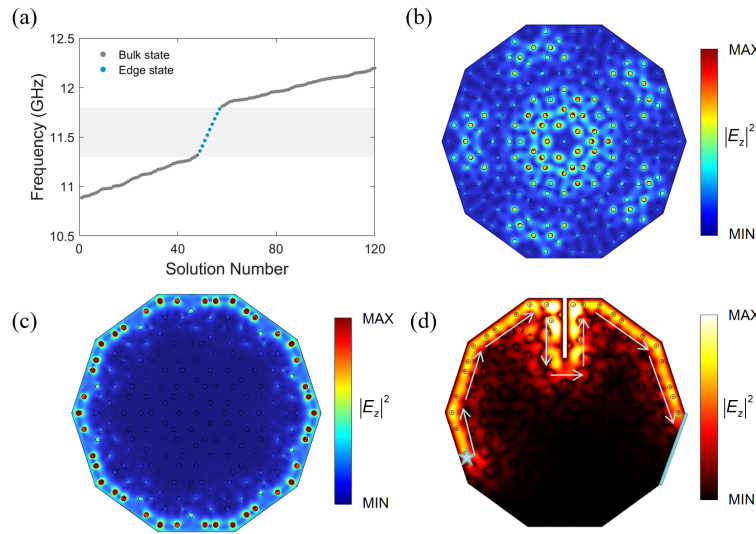


Fig. 2. Complete photonic band gap and chiral edge states in the topological photonic quasicrystal. (a) Calculated eigenmode spectrum of the topological photonic quasicrystal with PEC boundary conditions. The bulk (edge) states are represented by grey (blue) dots and the grey region represents the topological photonic band gap. (b) Simulated electric intensity profile of the bulk eigenstates. (c) Simulated electric intensity profile of the edge eigenstates. (d) Unidirectional and backscattering-immune propagation of the photonic chiral edge states in the topological photonic quasicrystal. The point source is represented by a blue star and the perfect absorption boundary condition is marked by a blue line.

3. Experimental observation of photonic chiral edge states

Now we start experimentally observing the photonic chiral edge states in a gyromagnetic photonic quasicrystal. The fabricated experimental sample is shown in Fig. 3(a), which consists of two layers of perforated aluminum plates as the top and bottom PEC boundary conditions and one

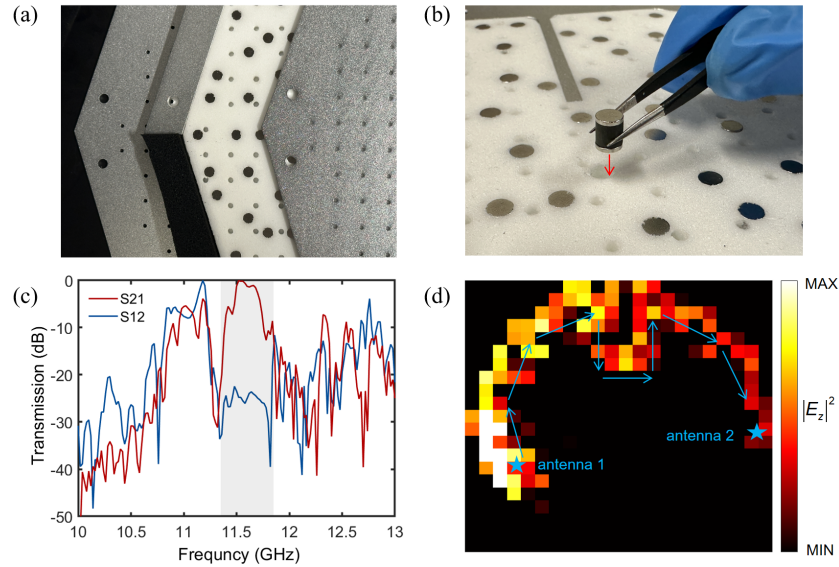


Fig. 3. Experimental observation of photonic chiral edge states in Penrose quasicrystal. (a) Photograph of the fabricated gyromagnetic photonic quasicrystal. The photonic quasicrystal is placed in a parallel plate waveguide, and the composited layers are glided for photographing. The black region is an electromagnetic wave absorber to absorb the photonic chiral edge states. (b) Magnified image of a gyromagnetic rod (black color) sandwiched between two permanent magnets (silver color) which are inserted into the perforated air foam to fix their position. (c) Measured clockwise (red line) and anticlockwise (blue line) transmission spectra of the photonic chiral edge states. The very high contrast between the clockwise and anticlockwise transmissions for frequencies in the photonic band gap (grey region) indicates the one-way transmission of the photonic chiral edge states. (d) Measured electric intensity distribution of the photonic chiral edge states at 11.5 GHz. The source and probe dipole antennas are marked as blue stars.

layer of perforated air foam (white color) inserted with gyromagnetic rods sandwiched between samarium cobalt (SmCo) permanent magnets, as shown in Fig. 3(b). The gyromagnetic photonic quasicrystal is surrounded by an aluminum plate working as the metallic cladding to prevent the leakage of the photonic chiral edge states. To measure the nonreciprocal transmission of the photonic chiral edge states, we use a two-port vector network analyzer (Keysight E5080) and a pair of dipole antennas to excite and probe the transmission spectrum (S₂₁ and S₁₂) of the photonic chiral edge states. The measured clockwise (red line) and anticlockwise (blue line) transmission spectra of the photonic chiral edge states are shown in Fig. 3(c), in which we observe a strong clockwise transmission approximately 30 dB greater than the anticlockwise transmission at frequencies within the photonic band gap (grey region), indicating the nonreciprocal transmission of the photonic chiral edge states. Finally, to test the robustness of the photonic chiral edge states, we insert a metallic obstacle in the propagation path and directly map the electric intensity distribution of the photonic chiral edge states at 11.5 GHz, as shown in Fig. 3(d), from which we can observe that the photonic chiral edge states smoothly circumvent around the metallic obstacle without any backscattering and radiation, matching well with the simulation results shown in Fig. 2(d).

4. Conclusion

In conclusion, we have experimentally observed photonic chiral edge states in a Penrose quasicrystal for the first time. By performing microwave transmission spectrum and near-field mapping measurements, we directly observe the nonreciprocal and robust transmission of the photonic chiral edge states in a gyromagnetic photonic quasicrystal. These results confirm that gyromagnetic photonic quasicrystals can also support photonic chiral edge states despite the absence of periodicity and translational symmetry. Since photonic quasicrystals exhibit arbitrary rotation symmetry [32,33], we expect rich topological photonic states to be waiting for exploration. Moreover, it will be very interesting to study the unique nontrivial properties of three-dimensional topological photonic quasicrystals [34–36] with topological surface, hinge, and corner states. Our work thus provides an ideal platform for investigating various novel topological states in photonic quasicrystals.

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Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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